Characterisation of Heat Losses in Zero Emission Buildings (ZEB) in Cold Climate

Johannes Brozovsky*, Niki Gaitani, Arild Gustavsen
Department of Architecture and Technology, NTNU, Trondheim, Norway

*Corresponding e-mail: johannes.brozovsky@ntnu.no

Abstract
It is well known that urban districts and neighbourhoods can form their own microclimate that can affect the energy balances of buildings significantly. In order to assess the effects of climatic parameters on a building’s performance, detailed knowledge about the energy balance of buildings is essential. In this study, the distribution of heat losses in a validated simulation model of a Zero Emission Building (ZEB) was analysed. The model was set to eight different cold climate locations and climate datasets to investigate the influence of wind and the building usage (residential and office building). The results show that in residential buildings envelope transmission, especially through windows and walls, dominate a typical ZEB’s energy losses. In office buildings, ventilation losses gain relevance due to more stringent requirements for ventilation rates. Wind sheltering can lower heat losses by 1.9 % to 8.3 %, depending on location and weather data.

Introduction
Climate and the environment where buildings are located determine their thermal behaviour and final energy use. Thus, it affects the selection of materials, technologies, concepts, or techniques in order to guarantee the buildings’ energy efficiency. Energy uses that are influenced by climate are primarily space heating and cooling. Space heating is responsible for around 70 % of final energy use (Building Performance Institute Europe, 2011).

It is widely accepted that urban microclimate and in particular the urban heat island (UHI), have a large influence on a building’s energy balance (Oke et al., 2017). Mainly, the UHI effect is described as a phenomenon to be mitigated, as it is regarded to obstruct the effectiveness of natural ventilation and to cause outdoor discomfort, higher need for cooling, or even higher mortality rates during summertime (Moonen et al., 2012). But the UHI is not necessarily detrimental but can be favourable especially in cold climate conditions, where heating energy use typically accounts for the largest fraction of a building’s energy demand over the year. Warmer night-time and winter temperatures can thus lead to lower heating demands and increased outdoor thermal comfort (Watkins et al., 2007). Most energy efficiency measures, such as the Energy Performance of Buildings Directive in the European Union (EU), focus on the building scale, demanding for example nearly zero energy buildings. The Research Centre on Zero Emission Neighbourhoods in Smart Cities (FME ZEN) however, pursues a different goal. Founded by the Norwegian University of Science and Technology (NTNU) and SINTEF, it aims to reach an overall zero emission balance over a neighbourhood’s life cycle (ZEN). Hence, ZENs and ZEBs are of particular importance for reaching the EU’s climate goals.

Figure 1: Polar and cold climate regions according to the data from Peel et al. (2007).
Therefore, characterizing the distribution of heat losses in a ZEB and their dependency on climate data will indicate, which microclimatic parameters are the most critical to address in the ZEN context. It can furthermore help architects and planners in the design of ZEBs with respect to different climate parameters.

Commonly, the heat losses of a building are categorized as follows:

- **Building envelope losses**
  
  are defined as the heat flux from inside to outside over the floor, roof, external walls, doors, windows, and thermal bridges. The losses are caused by heat transfer via conduction through the building parts, and convection as well as longwave radiation exchange on their inner and outer surfaces.

- **Infiltration losses**
  
  are unwanted flows of air through cracks and other passages in the building envelope. They cause additional energy use for heating the incoming outdoor air.

- **Ventilation losses**
  
  occur when outdoor air is supplied either via natural ventilation or a mechanical ventilation system (MVS) into the building. In order to keep losses as low as possible, often a heat recovery unit (HRU) is used.

**ZEB Living Laboratory**

The ZEB Living Laboratory (LL) is a 100 m² detached house test facility on the NTNU campus in Trondheim, Norway (see Figure 2 and Figure 3). As the name implies, zero emission buildings (ZEB) are not targeting energy use as a criterion, at least not primarily, but focus on the reduction of GHG-emissions, which are first and foremost responsible for climate change (Edenhofer, 2014). A ZEB aims to produce enough renewable energy to compensate for the building’s greenhouse gas emissions over its life span (Hestnes and Eik-Nes, 2017). This does not only demand the use of renewable energy on site but also promotes energy efficiency measures and the choice of building materials and products according to a life cycle assessment.

![Figure 2: Floor plan of the ZEB Living Laboratory.](image)

The LL was designed to host people for behavioural studies in interaction with zero emission technology. In several experiments, the building has been home for families, couples and single persons of different age and over different periods of time. The building is equipped with a heat pump, several smart home appliances, a PV system on the roof and several sensors to monitor the building’s energy consumption and production, and local weather conditions. The building envelope is well insulated and airtight. A double skin window with a ventilated gap is installed on the south façade (Goia et al., 2015). Table 1 shows the building-physical properties of the LL’s envelope.

**Table 1: Building-physical properties of the ZEB LL.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wall U-value</td>
<td>0.16</td>
<td>[W/(m²K)]</td>
</tr>
<tr>
<td>Floor U-value</td>
<td>0.11</td>
<td>[W/(m²K)]</td>
</tr>
<tr>
<td>Roof U-value</td>
<td>0.11</td>
<td>[W/(m²K)]</td>
</tr>
<tr>
<td>Windows (south) U-values</td>
<td>0.65/0.69</td>
<td>[W/(m²K)]</td>
</tr>
<tr>
<td>Windows (north) U-values</td>
<td>0.97</td>
<td>[W/(m²K)]</td>
</tr>
<tr>
<td>Windows (east/west) U-values</td>
<td>0.80</td>
<td>[W/(m²K)]</td>
</tr>
<tr>
<td>g-value</td>
<td>0.5</td>
<td>[-]</td>
</tr>
<tr>
<td>Infiltration n50</td>
<td>0.7</td>
<td>[ACH]</td>
</tr>
<tr>
<td>Normalized thermal bridge</td>
<td>0.03</td>
<td>[W/(m²K)]</td>
</tr>
</tbody>
</table>

Because in the following simulation results, heating demands will not be looked into, but only the heat balance of gains and losses, a detailed description of internal loads and occupancy is not necessary. To shorten the duration of the simulations, the existing heat pump model with its complex control strategies was replaced by a much faster simulating basic heating system, as this does not affect the distribution of the heat losses.

With regard to the MVS, the operation times and ventilation rates are of particular importance, as those will influence the ventilation losses. As a basis for the model, the Norwegian Standard SN/TS 3031:2016 has been used (see Table 2). The standard is the basis for calculating a building’s energy demand in a transient simulation program. On the one hand, by not adjusting the simulation model to the country-specific requirements, the distribution of heat losses is not fully realistic for the locations (except for Norway in this case). On the other hand, by using the same input data for the building, it is possible to highlight the effects of the locations’ climatic differences, on which this paper is focusing on.
The offset of 0.5 °C should not be considered detrimental, as they commonly do not induce the use of energy for heating. In analogy with the HLT, the solar gain threshold (SGT) temperature is 0.5 K below the cooling setpoint temperature (CST) of 24.0 °C (which is the CST according to SN/TS 3031:2016), as there is usually no need for cooling below this temperature, even though the building does not have a cooling unit. The offset of 0.5 K to HST and CST are necessary to avoid the heating system to be active during times, in which no losses are counted. Due to control behaviour, the HST will never be kept precisely at 21.0 °C but sway around it within a certain range (ca. ±0.1 K) and the heating system in the zones is active below 21.5 °C.

To keep indoor conditions within the desired limits, energy in the same magnitude as the losses has to be supplied to the building. Generally, in ZEBs, a large fraction of this energy comes from electrical appliances, lighting, persons or solar gains. Therefore, the amount of heat losses is not to be equated with the heating energy demand. For the calculation of heating energy to be supplied in addition, e.g. over radiators or surface heating. SN/TS 3031:2016 gives internal loads as high as 42 kWh/m²a for residential buildings and 72 kWh/m²a for office buildings. In the case of ZEBs, internal loads contribute significantly to covering the heating demand. For selecting the locations, available weather data of selected high latitude cities were analysed according to temperature variation, heating degree hours (HDH), since hourly weather data are used), annual global horizontal radiation and mean wind speed (see Figure 5).
Figure 5: Comparison of locations with regard to a) temperature range and average; b) annual global horizontal radiation; c) HDH\textsubscript{21/15}; d) mean wind speed.

HDH\textsubscript{21/15} describe the sum of hourly temperature differences between inside and outside over the year when hourly mean outdoor temperatures drop below 15 °C at an indoor temperature of 21 °C.

The study aims to evaluate heat losses in buildings for typical weather conditions in high latitude cold climate regions. Due to the distribution of landmass, these regions are mostly located on the northern hemisphere, except for Antarctica. The locations were selected according to the following two criteria:
- Latitude of at least 60° N
- Significant population or climate

The city of Oslo, however, located at 59.9° N was also included, as parts of the urban agglomeration and the site of the weather station at Oslo airport are located over 60° N. Apart from Barrow, which was included due to its harsh and severe climate conditions, all cities have rather large populations (from \(1.7 \times 10^4\) in Kiruna to over \(1.0 \times 10^6\) for the agglomeration of Oslo). Other large cities over 60° N like for example Reykjavik in Iceland, Helsinki in Finland, Murmansk in Russia or the large cities in North America have not been included since their climate was too similar to the already selected locations.

This study evaluates where heat losses in ZEBs in cold climate occur, how they are distributed, and which climatic parameters influence them the most. The results will then deliver valuable information, which measures in terms of a neighbourhood setting may be most effective concerning its energy use. This study’s outcome will then be used for further, more detailed investigations on the most important microclimatic parameters.

**Simulation cases**

As mentioned before, a central part of this study is the analysis of the influence of different wind conditions on the building’s energy balance. This will be done for the LL as a residential (R) and an office building (O). The basis for this investigation is the wind speed and direction from the weather file. The wind speed at the building site (roof height, \(V_{\text{loc}}\)) is then calculated by the IDA ICE with the reference wind speed from the climate data set (\(V_{\text{ref}}\)) the coefficients \(a_0\) and \(a_{\text{exp}}\), and the quotient of building height \(h_b\) to the reference height \(h_{\text{ref}}\) of the wind measurement, as in Eq. 1 (Bring et al., 1999). The coefficients \(a_0\) and \(a_{\text{exp}}\) can be chosen from a database, as listed in Table 3, but can also be defined individually.

Furthermore, pressure coefficients according to AIVC (sheltered, semi exposed, exposed) can be used. In the following simulations, three cases will be analysed:

1. “Open country” wind profile with “exposed” pressure coefficients (OC/E),
2. “Suburban” wind profile with “semi-exposed” pressure coefficients (SU/SE), and
3. “City centre” wind profile with “sheltered” pressure coefficients (CC/S)

\[
V_{\text{loc}} = V_{\text{ref}} \cdot a_0 \cdot \left(\frac{h_b}{h_{\text{ref}}}\right)^{a_{\text{exp}}} \quad (1)
\]
Figure 6: Distribution of heat losses for the residential building (R) and office building (O) for different locations and wind conditions: suburban/semi-exposed (SU/SE), open country/exposed (OC/E) and city centre/sheltered (CC/S).

Table 3: IDA ICE wind profile database according to ASHRAE 1993.

<table>
<thead>
<tr>
<th>Location</th>
<th>a0</th>
<th>aexp</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ocean</td>
<td>1.30</td>
<td>0.10</td>
</tr>
<tr>
<td>Airport</td>
<td>1.00</td>
<td>0.15</td>
</tr>
<tr>
<td>Open country</td>
<td>0.85</td>
<td>0.20</td>
</tr>
<tr>
<td>Suburban</td>
<td>0.67</td>
<td>0.25</td>
</tr>
<tr>
<td>City centre</td>
<td>0.47</td>
<td>0.35</td>
</tr>
</tbody>
</table>

Results

Figure 6 displays the heat balance of the ZEB LL for the investigated cases in the eight selected locations. While in Bergen comparably little heat is lost, the extreme winter conditions in Barrow result in more than three times the energy losses in the residential (R) case and four times as much in the office (O) case. The results show that the different wind conditions (OC/E, SU/SE, CC/S) influence a ZEB’s energy balance in cold climate mostly relatively little (see Table 4).

Table 4: Maximum reduction of heat losses through wind sheltering (OC/E compared to CC/S)

<table>
<thead>
<tr>
<th>Location</th>
<th>Residential</th>
<th>Office</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oslo, NOR</td>
<td>−3.6%</td>
<td>−3.6%</td>
</tr>
<tr>
<td>Bergen, NOR</td>
<td>−6.8%</td>
<td>−6.3%</td>
</tr>
<tr>
<td>Trondheim, NOR</td>
<td>−4.8%</td>
<td>−4.6%</td>
</tr>
<tr>
<td>Tromsø, NOR</td>
<td>−7.2%</td>
<td>−6.4%</td>
</tr>
<tr>
<td>Kiruna, SWE</td>
<td>−4.4%</td>
<td>−4.1%</td>
</tr>
<tr>
<td>Fairbanks, USA</td>
<td>−2.3%</td>
<td>−1.9%</td>
</tr>
<tr>
<td>Barrow, USA</td>
<td>−7.3%</td>
<td>−6.0%</td>
</tr>
<tr>
<td>Vorkuta, RUS</td>
<td>−8.3%</td>
<td>−7.0%</td>
</tr>
</tbody>
</table>

Compared to the OC/E case, wind sheltering (CC/S) reduces energy losses only by 1.9 % (O) to 2.3 % (R) in Fairbanks, since its winter climate is characterized by low wind speeds. In contrast to that, even though mean wind speed in Barrow is even higher, savings of 7.0 % (O) to 8.3 % (R) can be obtained from proper wind sheltering in Vorkuta, because high wind speeds predominantly coincide with low outdoor temperatures.

Unsurprisingly infiltration losses are largely influenced by wind conditions. Compared to CC/S, wind-induced infiltration in OC/E-conditions doubled in Fairbanks and quadrupled in Bergen with an average increase of 222.6 % (see Figure 7). There were no notable differences between the LL as a residential or an office building.
Building envelope and ventilation losses remained relatively stable (changes below 2%), even though wind speed is considered by the BEPS tool for the calculation of convective heat transfer coefficients. Figure 8 shows the envelope and infiltration heat losses as a function of the HDH12/15. The losses caused by the thermal bridges, floor, roof, walls and doors and windows show a strong dependency on HDH12/15 with $R^2$ close to 1. Infiltration losses correlate with HDH12/15 with an $R^2$ of 0.821 as they partly also correlate with wind speed. From the slope of the linear regression line in Figure 8, it is visible that the losses from windows and doors are stronger influenced by outdoor temperature.

$$y = -7E-08x^2 - 0.0029x - 241.05$$

$R^2 = 0.986$

Figure 8: Envelope and infiltration losses as a function of HDH12/15 of the ZEB LL as a residential building with SU/SE wind conditions

When looking at the ventilation losses, the relationship to HDH12/15 is not linear but exponential (see Figure 9). Whereas in Barrow, losses through the roof and the wall are about three times higher than in Bergen, ventilation losses differ with the factor 5.

Windows take a special role in the energy balance of a building, as they can account for significant amounts of solar energy gains. Figure 10 illustrates the proportion of gains and losses in the respective locations. Especially in the Norwegian cities with around 40% of the total heat losses, useful solar gains significantly enhance the windows’ overall energy balance. In Barrow, the highest amount of useful gains can be obtained, but losses outweigh the gains by the factor 5.5.

Table 5: Overview of total heat losses of the ZEB LL in different locations as residential and office buildings in SU/SE wind conditions.

<table>
<thead>
<tr>
<th>Location</th>
<th>Residential [kWh/a]</th>
<th>Office [kWh/a]</th>
<th>Difference [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oslo, NOR</td>
<td>-9 011</td>
<td>-9 756</td>
<td>-8.3 %</td>
</tr>
<tr>
<td>Bergen, NOR</td>
<td>-7 265</td>
<td>-7 837</td>
<td>-7.9 %</td>
</tr>
<tr>
<td>Trondheim, NOR</td>
<td>-8 025</td>
<td>-8 725</td>
<td>-8.7 %</td>
</tr>
<tr>
<td>Tromsø, NOR</td>
<td>-10 695</td>
<td>-11 607</td>
<td>-8.5 %</td>
</tr>
<tr>
<td>Kiruna, SWE</td>
<td>-14 091</td>
<td>-15 498</td>
<td>-10.0 %</td>
</tr>
<tr>
<td>Fairbanks, USA</td>
<td>-15 715</td>
<td>-17 757</td>
<td>-13.0 %</td>
</tr>
<tr>
<td>Barrow, USA</td>
<td>-26 865</td>
<td>-31 297</td>
<td>-16.5 %</td>
</tr>
<tr>
<td>Vorkuta, RUS</td>
<td>-20 271</td>
<td>-23 147</td>
<td>-14.2 %</td>
</tr>
</tbody>
</table>

Figure 10: Unwanted losses and useful solar gains of windows in the ZEB LL as a residential building with SU/SE wind conditions.

Discussion

The IDA ICE simulations show a considerable variation of the distribution of heat losses, depending on the location’s climate and the building’s usage. Extremely low outdoor air temperatures affect ventilation losses stronger than e.g. envelope losses. The MVS and the HRU in particular face the problem of building up ice at very low temperatures and/or high moisture loads (Justo Alonso et al., 2015). In case of the ZEB LL, the HRU can operate until ca. −15 °C at full efficiency without building up ice. Below this temperature, preheating the air clearly deteriorates the overall efficiency and leads to a nonlinear correlation. While in the oceanic dominated climates of coastal Scandinavia, those extreme conditions occur only at rare intervals, the continental climate of its inland, central Alaska, or Siberia results in longer periods of extreme frost with temperatures dropping to −30 or even −40°C. Because of higher requirements for ventilation rates in office spaces from the Norwegian building code (NBC), ventilation losses are considerably higher. In all locations, windows account for a large fraction of heat losses.
losses, when only losses from conduction and longwave radiation are considered. The useful solar gains of west and east-oriented windows compensate for around 50% of unwanted losses over the year in the Norwegian cities. South-oriented windows can even have a positive energy balance with over 20% more useful energy gains than unwanted losses. These results support the findings by Grynning et al. (2013) that a window can outperform opaque building parts even in high-latitude locations when window properties, orientation etc. are chosen appropriately. Unwanted solar gains during summertime, on the other hand, increase the risk of overheating. This issue has not been considered in this study, though it generally should not be disregarded. In the non-Norwegian locations, none of the ZEB LL’s windows came close to a positive annual energy balance.

Floor and roof of the LL account for large fractions of total the total envelope area, as it only consists of one storey (building envelope area A to volume V ratio A/V = 1.1 m⁻¹). Therefore, these building parts also account for a high share of the building’s total heat losses. In larger multi-storey residential or office buildings, the envelope losses will account for a lower fraction of total heat losses (with A/V as low as 0.2 m⁻¹), which puts more importance on ventilation losses as they are a function of a building’s floor area. The distribution of heat losses for the ZEB LL in the different locations can be seen in Figure 11 and Figure 12.

It is worth noting that floor losses in IDA ICE are calculated according to ISO 13370 (International Standard Organisation, 2017). The program determines the heat resistance of the ground layer based on the geometry of the building and the heat conductivity of the ground material (kept at its default values with thermal conductivity λ = 2.0 W/(mK), density ρ = 2000 kg/m³, and heat storage capacity c = 1000 kJ/kg). According to ISO 13370, the ground temperature is calculated as a weighted average value of the annual and the monthly mean air temperatures, including a given time lag.

However, the study is limited by the fact that the ZEB LL cannot be regarded as a typical office building. In addition, the results are not generalisable for single-family homes in the selected locations either, apart from the Norwegian ones because input parameters for the simulations are based on the NBC. Country-specific regulations in the non-Norwegian locations would certainly lead to different results. However, because the focus in this study was put on the influence of climate, results are only comparable when using an identical input.

Other limiting aspects are the weather data. Mostly, they have been recorded at the locations’ airports, often more than 20 km away. The wind situations there may be entirely different from what an average building in the cities might experience. The same limitation applies to solar irradiation, as no mutual shadowing was accounted for in this study. Beyond, especially when it comes to the influence of wind, BEPS programs are not very well suited for meaningful quantitative analyses. For that, computational fluid dynamics (CFD) programs should be used to evaluate reasonable boundary conditions. Moreover, this study is based on self-defined thresholds as there are no official definitions of useful gains and unwanted or detrimental losses. Different definitions may, therefore, lead to different results.

**Conclusion**

In this study, a validated model of the ZEB Living Laboratory, located on the campus of the Norwegian University of Science and Technology in Trondheim, Norway, was simulated at different locations in cold climate to analyse the distribution of heat losses. While envelope and infiltration losses were found to be linearly dependent on the number of heating degree hours, ventilation losses revealed to have an exponential relationship. When using the Norwegian building code for the input parameters, the main difference between residential (R) and office (O) building was found to be the ventilation losses due to more stringent requirements for ventilation rates in offices.

Whereas the presented results might seem rather self-evident, such quantitative analysis of heat losses in a ZEB in cold climate conditions can be regarded as the first step towards a comprehensive analysis of microclimatic effects on ZEBs and delivers useful information on how heat losses are distributed. The setting of a Zero Emission Neighbourhood not only impacts the wind sheltering situation which is able to reduce heat losses by 1.9% (O) to 2.3% (R) in Fairbanks and 7.0% (O) to 8.3% (R) in Vorkuta.

![Figure 11: Distribution of heat losses for the ZEB LL as a residential building for SU/SE wind conditions.](image-url)
Figure 12: Distribution of heat losses for the ZEB LL as an office building for SU/SE wind conditions.

It also influences solar accessibility, which was found to account for significant amounts of solar gains. Windows can, in fact, outperform opaque building parts, even in high-latitude locations.

Additional investigations of different kinds of buildings, regarding their shape, usage and material properties need to be carried out to further quantify the impact of microclimatic aspects on a ZEB’s energy balance. For that, measurements and simulations are currently carried out on FME ZEN’s pilot projects as case studies.

Acknowledgements

This paper has been written within the Research Centre on Zero Emission Neighbourhoods in Smart Cities (FME ZEN). The authors gratefully acknowledge the support from the ZEN partners and the Research Council of Norway.

References


Norwegian Building Authority (2017): Regulations on technical requirements for construction works.


